IONIZATION OF E-LAYER BY X-RAYS

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ABSTRACT. In this paper, the transmission curves for solar radiations in the X-ray and ultraviolet regions through the earth's atmosphere, obtained from rocket data and absorption coefficients have been utilized for determining the radiation responsible for E-layer ionization. It is found that only X-rays between the wavelength region 5 to 100A are absorbed in the region of the atmosphere occupied by E-layer. The amount of energy absorbed is 0.19 erg cm^{-2} sec^{-1}. The number of ions produced by (1) absorbed X-rays, (2) ejected photoelectrons produced by X-rays, and (3) Auger Effect induced by X-rays has been calculated and found to be 4×10^{8}, 5.6×10^{9}, and 2.5×10^{8} cm^{-2} sec^{-1} $column^{-1}$ respectively or the total rate of production of ions in the E-layer is 6.2×10^{9} cm^{-2} sec^{-1} $column^{-1}$. Remembering the error in the measurements of energy from a rocket, this value agrees with that obtained from substituting the value of effective recombination coefficient and electron density for E-layer in the expression $q = \alpha N_e^2$.

The temperature of the sun corresponding to different wavelength regions are calculated from data obtained from rocket-borne experiments. The calculated values agree with those given by Nicolet.

1. INTRODUCTION

E. O. Hulburt (1938) was the first to propose that soft X-rays may produce the E-region. Bates and Hoyle (1948) supported Hulbert's proposal. In considering auroral phenomena, Vegard (1923, 1938) also suggested that soft X-rays are a major contributor to the ionization at high altitudes. Also, from solar energy measurements by rocket-borne experiments, it appears that ionization of the E-layer is due to soft X-ray emissions from solar corona. Recently, Friedman (1959) suggested that E-region is produced by X-rays and Lyman-β (1025A), and D-region by Lyman-α (1216Å).

In this paper, the total amount of solar X-ray energy absorbed within the E-layer is calculated from the energy at the top of the earth's atmosphere obtained from rocket-borne experiments and the transmission curves for these radiations through the atmosphere. The rate of ionization produced by absorbed energy is then calculated and compared with other available value.

The temperatures of the sun at different spectral regions in the ultraviolet and X-rays are also calculated from the amounts of solar energy at the top of the earth's atmosphere, obtained from rocket-borne experiments.

2. TRANSMISSION CURVES FOR X-RAYS AND ULTRA-VIOLET RADIATIONS

Fig. 1 shows the transmission of different wave-lengths through the earth's atmosphere. The solid curves (Friedman, 1959) represent the penetration of solar radiations into the atmosphere for vertical incidence obtained from rocket-borne experiments. The dot-dash curves (Byram *et al.*, 1954) show the penetration of certain radiations computed from absorption coefficients given by Compton and Allison (1953). Dotted line curves (Friedman *et al.*, 1951) represent the transmission of solar radiations observed from V-2 49 rocket using photon counters.

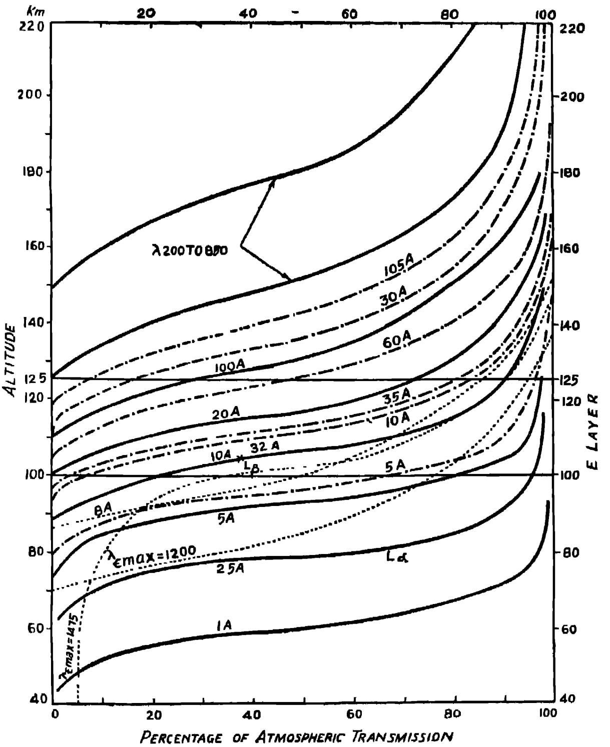

Fig. 1. Atmospheric transmission for different wavelengths in the X-ray and ultraviolet regions. The solid curves (Friedman, 1959) are obtained from rocket-borne experiments. Dotted line curves (Friedman, 1951) are also obtained using photon counters in V-2 49 rocket. Dot-dash curves are computed from absorption coefficients given by Compton and Allison.

It will be seen from above curves that, in general, radiations penetrate deeper into the atmosphere as the wavelength decreases. There are, however, certain departures. Wavelengths 1475A, Lyman-α, 1200A and Lyman-β penetrate much deeper into the earth's atmosphere. In the dot-dash curves, wavelength 30 A penetrated to a lesser depth compared to wavelengths 35A, 60A and 100A. Also, it may be noted that Lyman-α, and 2.5A, and wavelengths 10A and 32A have the same penetrating characteristics.

From the nature of these transmission curves, one can easily conclude that different amounts of energy corresponding to different wavelengths are absorbed at different altitudes of the atmosphere. Wavelengths from 200 A to 850 A are absorbed above 125Km, whereas those between 5A and 100A are absorbed in the region 90-125 Km. The Lyman-α radiation (Byram *et al.*, 1953) penetrates upto 74 $\pm$ 2 Km. Also, Lyman-β is absorbed between altitudes 90 and 125 Km. Wavelength 2.5A penetrates below 70 Km and 1A well below 60 Km.

From rocket data, 50 per cent transmission of energy at different wavelengths in the X-ray region is calculated and is shown in Fig. 2. The values given by Leo Goldberg (1954) for 50 per cent transmission of energy for higher wavelengths are also given in the same figure.

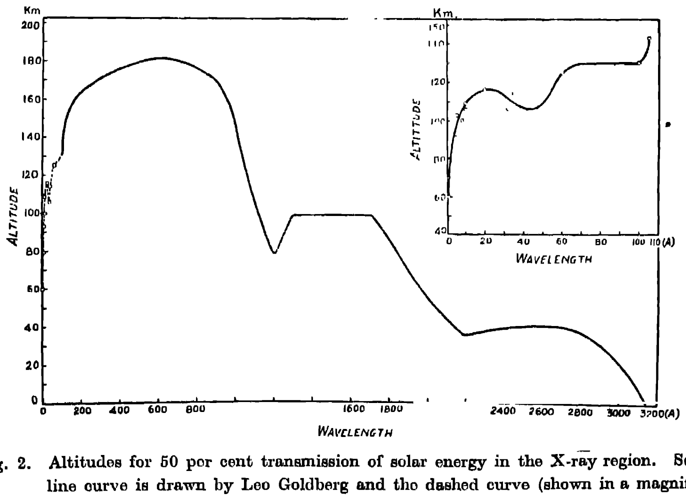

Fig. 2. Altitudes for 50 per cent transmission of solar energy in the X-ray region. Solid line curve is drawn by Leo Goldberg and the dashed curve (shown in a magnified scale on the right side) is obtained from the present work.

3. ABSORPTION OF X-RAYS IN E-LAYER

The results of measurements of electron density as obtained from different rocket flights at White Sands Proving Ground, New Mexico, are given in Table 1.

These measurements show that the height of the maximum ionization of the *E*-layer lies between 100 and 110 Km. It has also been observed that under normal conditions of the sun there is not much variation in electron density up to 125 Km, although during solar activity there is considerable variation. Therefore, for calculating the number of ion cm^{-2} sec^{-1} $column^{-1}$, the *E*-layer may be assumed to lie between 100 and 125 Km.

TABLE I

E-layer ionization from rocket data at white sands proving ground, New Mexico

Rocket flight, date and time	Authors	Altitude of maximum ionization Km	Remarks
May 7, 1947; 11-25 hrs. MST		About 110	Rapid increase in electron density from 85 Km to 110 Km; no measurement was made above 110 Km.
Jan. 22, 1948; 13-14 hrs. MST		100	Electron density increases from 92 Km to 100 Km. No data available above 100 Km.
V-2 No. 49, Sept. 29, 1949; 10-00 hrs. MST		107	Peak electron density at 107 Km. Between 110 and 125 Km, there is not much variation in electron density.
Viking No. 5, Nov. 21, 1950; 10.18 hrs. MST		110	Electron density gradient becomes steep from about 92 Km. Peak electron density is observed at 110 Km. There is not much variation in electron density between 110 and 125 Km.
Viking No. 10, May 7, 1954; 10-00 hrs. MST	*b*	Peaks at 101, 112 and 129	Measurements show a rapid increase in electron density at 91 and 101 Km.
Aerobee-38, June 26, 1953; 12.10 hrs. MST	*c*		A sharp maxima at 110 Km.
Aerobee-HI NRL-50, June 29, 1956; 12-09 hrs. MST	*d*	Sharp maxima at 101	Electron density increases from 92 to 160 Km. Between 100 and 125 Km, the electron density is practically constant.

a—Jackson, 1954 & Seddon, 1954 ; *b*—Seddon *et al.*, 1954 ; & Jackson, 1956 ; *c*—Pfister *et al.*, 1958 ; *d*—Jackson *et al.*, 1958.

Solar energy values at the top of the earth's atmosphere for different wavelengths were obtained from rocket flights and are shown in Section 5 (Table 4). The percentage of absorption of these radiations in the *E*-layer was calculated from Fig. 1. Assuming the *E*-layer to lie between altitudes 100-125 Km, the energy absorbed in this layer corresponding to different wavelengths is then calculated and is given in Table II. A graph is drawn between the absorbed energy and wavelengths and is shown in Fig. 3. The integrated area gives the total amount of X-ray energy absorbed in the *E*-region. Its value is estimated to be 0.19 erg cm^{-2} sec^{-1}. [The Lyman-β (λ 1025) radiation is also absorbed between

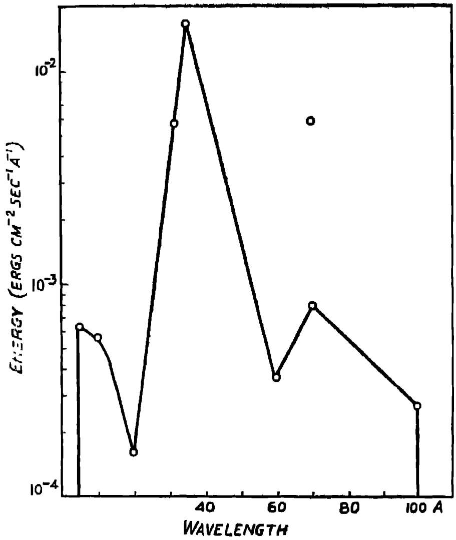

Fig. 3. The solar energy in the X-ray region absorbed in the E-layer as calculated from Fig. 1. The E-layer is assumed to lie between altitudes 100 and 125 Km. Corresponding to 70 Å two energy values, 2×10^{-3} and 1.5×10^{-2} ergs cm^{-2} sec^{-1} A^{-1} were obtained by Friedman (1959). In the present calculations only the lower value is taken.

the altitudes 100-125 Km. However,it does not produce *E*-layer ionization because it requires radiations of wavelength less than 1019A].

TABLE II

Solar energy in the X-ray region absorbed between altitudes 100 and 125 Km

Wavelength (A)	Percentage of energy absorbed	Energy absorbed (erg cm^{-2} sec^{-1} A^{-1})
5	25	6.25×10^{-4}
10	75	5.63×10^{-4}
20	75	1.62×10^{-4}
32	70	5.81×10^{-3}
35	85	1.70×10^{-2}
60	50	3.75×10^{-4}
70	40	8.00×10^{-4}
100	30	2.70×10^{-4}

4. IONIZATION IN E-LAYER BY X-RAYS

Assuming that X-rays absorbed in the E-layer are responsible for its ionization, the number of ions produced in this layer has been calculated as follows :

The amount of energy absorbed in the E-layer in an interval of 5A has been obtained from Fig. 3. The mean photon energy in the interval is then calculated. Dividing the former by the latter gives the number of photons. Knowing the number of photons in the interval of 5A, the rate of production of ions* in the E-layer by X-rays emitted by the sun has been calculated.

The rate of production of 0^+ ions, $q(0^+)$, will depend upon the product of absorption coefficient, α_0, of 0 atoms corresponding to frequency ν and its concentration, $n(0)$. Therefore,

$$q(0^+) \propto \alpha_0 n(0). \qquad \dots (1)$$

Similarly, in the case of nitrogen atoms

$$q(N^+) \propto \alpha_N n(N). \qquad \dots (2)$$

Therefore,

$$\frac{q(N^+)}{q(0^+)} = \frac{\alpha_N n(N)}{\alpha_0 n(0)} \qquad \dots (3)$$

or,

$$q(0^+) = \frac{\alpha_0 n(0)[q(0^+)+q(N^+)]}{\alpha_0 n(0)+\alpha_N n(N)} \qquad \dots (4)$$

Substituting A for $[q(0^+)+q(N^+)]$ which is the total rate of production of ions in the E-layer or the number of photons absorbed, the Eqn. (4) becomes

$$q(0^+) = \frac{\alpha_0 n(0)}{\alpha_0 n(0)+\alpha_N n(N)} \times A.$$

Similarly,

$$q(N^+) = \frac{\alpha_N n(N)}{\alpha_0 n(0)+\alpha_N n(N)} \times A.$$

The absorption coefficients of atomic oxygen and nitrogen have been taken after Compton and Allison (1953) and the particle concentration after Nicolet (1959). The ejected photoelectrons are loaded with excess energy and cause valence ionization of other atoms. Also, from Auger Effect for K-L shell transition for 0 and N atoms there exists 50 per cent probability of electron ejection and

* The photons corresponding to wavelengths $\leqslant$ 23.58 A and 31.18 A, eject K electrons from oxygen and nitrogen atoms respectively, while those corresponding to wavelengths greater than the above values eject L electrons.

50 per cent for X-ray emission. The rates of ion production by the above processes are given in Table III.

TABLE III

Ion production due to X-rays in the *E*-layer by different processes

	K-shell ionization	L-shell ionization	Valence shell ionization	Ionization by Auger Effect	
				Direct electron ejection	From X-ray emission
	($cm^{-2}s^{-1}col^{-1}$)	($cm^{-2}s^{-1}col^{-1}$)	($cm^{-2}s^{-1}col^{-1}$)	($cm^{-2}s^{-1}col^{-1}$)	($cm^{-2}s^{-1}col^{-1}$)
Oxygen	2.5×10^{6}	1.6×10^{8}	2.2×10^{9}	1.2×10^{6}	2.4×10^{7}
Nitrogen	1.8×10^{7}	2.2×10^{8}	3.4×10^{9}	8.8×10^{6}	2.2×10^{8}
Total	2.0×10^{7}	3.8×10^{8}	5.6×10^{9}	1.0×10^{7}	2.4×10^{8}

Therefore, the average rate of ion production in the *E*-layer is 6.2×10^{9} cm^{-2} sec^{-1} column^{-1}.

Another value for the rate of production of ions can be obtained by substituting the values of α and Ne in the expression for the rate of production of ions at equilibrium condition, namely,

$$q = \alpha Ne^2 \qquad \ldots \quad (5)$$

where,

q—rate of ion production,

α—effective recombination coefficient,

and Ne—ionization density.

The value of α as given by different investigators (Appleton, 1959 ; Landmark, 1956) ranges from 1×10^{-8} to 4×10^{-8} cm^3 sec^{-1}. The calculated value of the rate of total ion production due to X-rays agrees with the value obtained from the expression (5) if $\alpha = 6\times10^{-8}$ cm^3 sec^{-1} and $Ne = 2\times10^{5}$ cm^{-3}. It may, however, be noted that the transmission curves (Fig. 1) were plotted from the data obtained from rocket-borne experiments by using photon counters and thermoluminescent phosphor technique. These data are liable to be in error. The measurements with photographs and ion chambers give more accurate values for the energy (Friedman, 1959 ; Jager, 1959).

5. TEMPERATURE OF SUN IN X-RAY AND ULTRA-VIOLET REGIONS

We have already seen in Section 3 that the energy values at the top of earth's atmosphere corresponding to different wavelengths from ultraviolet to X-rays are obtained from rocket-borne experiments. From these energy values and considering the sun as a black body radiator, the coronal temperatures corresponding to the emission of X-rays and ultraviolet radiations have been computed following the method of Nicolet (1952) as follows.

If $\rho(\nu)$ be the density of radiation emitted by the sun, then from Planck's formula

$$\rho(\nu) = \frac{8\pi h\nu^3}{C^3}(e^{h\nu/kT}-1)^{-1},$$

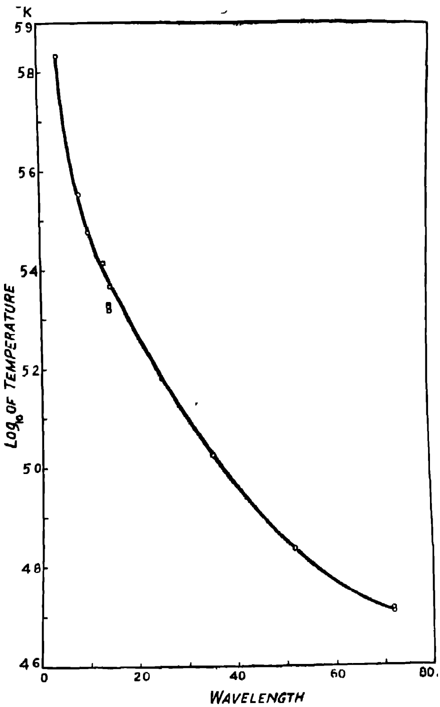

Fig. 4. Variation of temperature of the sun with wavelength in the X-ray region obtained from rocket data.

where the symbols have their usual significance. The radiation density $\rho'(\nu)$ at the top of the atmosphere is given by the relation

$$\rho'(\nu) = \beta_s \cdot \rho(\nu),$$

TABLE IV

Equivalent black body temperatures of the sun obtained from rocket-borne experiments in the X-ray and ultraviolet regions

Wavelength region (A)	Author	Condition of the sun	Energy (ergs cm^{-1} sec^{-1})	Equivalent black body temperature (°K)
Below 8	*a*	late in class I flare	5×10^{-3}	6.8×10^{5}
6—10	*b*	160 minutes after class I flare	$10^{-4}-10^{-3}$	3.5×10^{5}
8—12	*c*	quiet	3×10^{-3}	3.0×10^{5}
8—18	*d*	high coronal activity	0.6	2.6×10^{5}
8—20	*c*	-do-	0.1	2.3×10^{5}
8—20	*a*	quiet	1.5×10^{-3}	2.1×10^{5}
8—20	*a*	-do-	1.3×10^{-3}	2.1×10^{5}
8—20	*a*	-do-	1.2×10^{-3}	$2\ 1\times10^{5}$
8—20	*a*	-do-	0.4×10^{-3}	2.1×10^{5}
10—60	*d*		1.0	1.1×10^{5}
44—60	*e*	minimum solar activity	1.4×10^{-2}	6.8×10^{4}
44—100	*e*	-do-	3.5×10^{-2}	5.2×10^{4}
44—100	*e*	-do-	2.9×10^{-2}	5.2×10^{4}
1050—1240	*f*	normal	0.4	5330
1200	*b*	-do-	6.2×10^{-2}	(6000)*
1216	*g*	no unusual solar activity	6.3	7730
1150—1340	*b*	-do-	1—10	5630
1230—1340	*b*	-do-	0.2	4840
1500	*b*	-do-	5.4×10^{-3}	(4500)*
2050	*h*	-do-	3.7	(5000)*

a—Chubb *et al.*, 1957 ; *b*—Friedman *et al.*, 1951
c—Burnight, 1952 ; *d*—Byram *et al.*, 1954 ;
e—Byram *et al.*, 1956 ; *f*—Tousey *et al.*, 1951.
g—Jager, 1959 & *h*—Byram *et al.*, 1952.

For figures marked with * the amounts of energy have been calculated from the given temperatures.

where the dilution coefficient β_s is given by

$$\beta_s = \frac{R^2}{4r^2} = \frac{(\text{sun radius})^2}{4(\text{sun-earth distance})^2}$$

$$= 5.41 \times 10^{-6}.$$

The temperatures thus calculated are given in Table 4. Comparing these values with the equivalent black body temperatures calculated by Nicolet (1952) from the coronal radiation of the quiet sun given in Table V, we find that there is a fair agreement between the two sets of values. The variation of temperature with wavelengths in the X-ray region is shown in Fig. 4. It may, however, be pointed out that the emission from the sun may be of grey body type (Byram *et al*, 1956). If such be the case, the actual temperature will be higher than those given in Table IV.

TABLE V

Equivalent black body temperatures of quiet sun in the X-ray and ultraviolet regions obtained by Nicolet

Wavelength (A)	Equivalent black body temperature (°K)
4	5.0×10^5
10	3.0×10^5
14	2.0×10^5
20	1.6×10^5
21.5	1.5×10^5
29.6	1.2×10^5
50	7.5×10^4
75	5.0×10^4
200	2.0×10^4
228	1.9×10^4
250	1.8×10^4
500	7.0×10^3
910	5.0×10^3
1000	5.0×10^3

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